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SOCIETAL LIFE CYCLE ASSESSMENT

Integration of working environment into life cycle assessment framework

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Abstract

Background, aim, and scope Life cycle assessment (LCA) has been considered one of the tools for supporting decision-making related to the environmental aspects of a product system. It has mainly been used to evaluate the potential impacts associated with relevant inputs and outputs to/from a given product system throughout its life cycle. In most cases, LCA has not considered the impacts on the internal environment, i.e. working environment, but only the external environment. Recently, it has been recognized that the consideration of the impacts on the working environment as well as on the external environment, is needed in order to assess all aspects of the effects on human well-being. To this end, this study has developed a total environmental assessment methodology which enables one to integrate both the working environment and the external environment into the conventional LCA framework.

Materials and methods In general, the characteristics of the impacts on the external environment are different from those on the working environment. In order to properly integrate the two types into total environmental impacts, it is necessary to define identical system boundaries and select impact category indicators at the same level. In order to define the identical system boundary and reduce the uncertainties of LCI results, the hybrid IOA (input–output analysis) method, which integrates the advantages between conventional LCI method and IOA method, is introduced to collect input and output data throughout the entire life cycle of a given product. For the impact category indicators at the endpoint level, LWD (Lost Work Days) is employed to evaluate the damage to human health and safety in the working environment, while DALY (disability-adjusted life years) and PAF (Potentially Affected Fraction) are selected to evaluate the damage to human health and eco-system quality in the external environment, respectively.

Results and discussion The environmental intervention factors (EIFs) are developed not only for the data categories of resource use, air emissions, and water emissions, but also for occupational health and safety to complete a life cycle inventory table. For the development of the EIFs on occupational health and safety, in particular, the number of workers affected by *i* hazardous items and the number of workers affected at the *i* magnitude of disability are collected. For the characterization of the impact categories in the working environment, such as occupational health and safety, the exposure factors, effect factors, and damage factors are developed to calculate the LWD of each category. For normalization, the normalization reference is defined as the total LWD divided by the total number of workers. A case study is presented to illustrate the applicability of the proposed method for the integration of the working environment into the conventional LCA framework.

Conclusions This study is intended to develop a methodology which enables one to integrate the working environmental module into the conventional LCA framework. The hybrid IOA method is utilized to extend the system boundary of both the working environment module and the external environment module to the entire life cycle of a product system. In this study, characterization models and category indicators for occupational health and safety are

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proposed, respectively, while the methodology of Eco-indicator 99 is used for the external environment. In addition to aid further understanding on the results of this method, this study introduced and developed the category indicators such as DALY, and LWD, which can be expressed as a function of time, and introduced PAF, which can be expressed as a probability.

Recommendations and perspectives The consideration of the impacts not only on the external environment, but also on the working environment, is very important, because the best solution for the external environment may not necessarily be the best solution for the working environment. It is expected that the integration of occupational health and safety matters into the conventional LCA framework can bring many benefits to individuals, as well as industrial companies, by avoiding duplicated measures and false optimization.

Keywords Disability-adjusted life years (DALY) · External environment · Hybrid IOA method · Lost work day (LWD) · Occupational health · Occupational safety · Societal life cycle assessment · Working environment

Abbreviations

BOD	biochemical oxygen demand
COD	chemical oxygen demand
DALY	disability-adjusted life years
DF	damage factor
EF	effect factor
EIF	environmental intervention factor
ExF	exposure factor
GDP	gross domestic product
GtG	gate-to-gate
IOA	input–output analysis
KEMCO	Korea Energy Management Corporation
KOSHA	Korea Occupational Safety and Health Agency
LCA	life cycle assessment
LCIA	life cycle impact assessment
LCI	life cycle inventory analysis
LWD	lost work days
MOD	magnitude of disability
MOE	Ministry of Environment
OD	occupational disease
PAF	potentially affected fraction
PRTR	pollutant release and transfer registers
SS	suspended solid
TDR	total domestic quantity of resources transported
TEA	total environmental assessment
T-N	total nitrogen
TNA	total national amount
T-P	total phosphorus
WHI	the number of workers affected by specific hazardous items
WMD	the number of workers proven to magnitude of disability

1 Background, aim, and scope

LCA has been considered one of the tools for supporting decision-making related to the environmental aspects of a product system. It has mainly been used to evaluate the potential impacts associated with relevant inputs and outputs to/from a given product system throughout its life cycle (International Standard ISO 14040 2006). In most cases, so far, LCA has not considered the impacts on the internal environment, i.e. working environment, only the external environment. As a result, is it worthwhile to integrate the working environment module into the conventional LCA frameworks? Ann-Beth Antonsson et al. insists that the inclusion of the working environment in LCA is needed to avoid false optimization (Antonsson and Carlsson 1994). Measures to reduce a product's effect on the external environment may result in a negative effect on the working environment. The best solution for the external environment is not always the best solution for the working environment and vice-versa (Antonsson and Carlsson 1994; Nilsson and Antonsson 1998). Potting et al. (1998) emphasize that the distinction and boundary between the external and working environment in LCA are artificial. The same agents may be emitted to the external as well as to the working environment and have an impact on the well-being of humans. Therefore, it saves time, and it is easier, to include and collect data for the working environment from the start of an LCA (Potting et al. 1998). It was also argued that the objective of an LCA is to assess all aspects of the effects on humans' well-being over a long-term period (Potting et al. 1998). Work plays an important role in well-being, and the working environment is presumably as important for the individual as is the external environment. In addition, it is reported that the integration of occupational health and safety matters into environmental management systems can bring many benefits to industrial companies (Honkasalo 2000). It can avoid duplicated measures and find optimal solutions because the principles of prevention are similar in both environmental protection and safety management.

As the significance of the impacts on the working environment as well as the external environment is recognized, several approaches such as Chemiewinkel, MUP, STØ IVL, IVF, EDIP methods, etc. have been developed in order to integrate the working environment module into the conventional LCA framework (Poulsen and Jensen 2004; Terwoert 1994; Schmidt et al. 1994; Rønning et al. 1995; Antonsson and Helene Carlsson 1995; Bengtsson and Berglund 1996; Hauschild and Wenzel

1998). Depending on their intended applications these approaches can be classified as a chemical screening method, sector method, or process method (Poulsen and Jensen 2004). A chemical screening method can be used to pinpoint the most important chemicals from a working environment perspective. Chemiewinkel, MUP and STØ methods are classified as the screening method (Terwoert 1994; Schmidt et al. 1994; Rønning et al. 1995). A sector method is an approach that is based on the working environmental impacts in a specific industrial sector. This approach mainly uses the statistical information from national sources. On the other hand, a process method is an approach that is based on company- or process-specific information. Thus, this method may give a more precise assessment than the other methods because it is based on the actual working environmental impacts. IVL and new EDIP methods are sector methods while IVF and EDIP methods can be considered as the process methods (Antonsson and Helene Carlsson 1995; Bengtsson and Berglund 1996; Hauschild and Wenzel 1998).

Depending on the system boundary considered, these methods can be defined as either a life cycle approach or a site approach. The STØ method considers the impacts from a specific site, while other methods include the impacts from the entire life cycle a product system (Rønning et al. 1995).

Depending on the types of the category indicators and characterization models selected for life cycle impact assessment (LCIA) along the environmental mechanism, the impacts on the working environment can be categorized as exposure-type impacts and effect-type (or damage-type) impacts. If, for example, the inventory parameters for the working environment such as vibration, noise, organic solvents and heavy metals are used for the exposure analysis, they are converted into exposure-type impacts to evaluate the potential impact of a given product system on working environment. On the other hand, the risks of accidents are used to provide the effect-type impacts for the evaluation of the actual endpoint impacts on the working environment. The STØ method evaluates the impacts on the working environment by using the exposure estimates for chemical substances, while the IVL method is to assess the impacts using the effect-type data for all impact categories (Rønning et al. 1995; Antonsson and Helene Carlsson 1995). The Chemiewinkel and IVF methods assess the impacts using both the exposure-type and the effect-type data (Terwoert 1994; Bengtsson and Berglund 1996).

It is recognized that the consideration of the impacts not only on the external environment, but also on the working environment is very important. To this end, this study has developed a total environmental assessment (TEA) methodology which enables one to integrate the aspects of both the external environment and the working environment into the conventional LCA framework. The input–output analysis (IOA) is utilized to extend the system boundary to the entire life cycle of a product system. In order to assess the effect-type impacts on the working environment at the endpoint level, the damage analysis, as well as exposure analysis, is carried out in this study. In addition, the practical feasibility of the proposed method is examined through a simple case study of a polystyrene production system in a Korean petrochemical company.

2 Proposed method

2.1 General requirements

In general, the characteristics of the impacts on the external environment are different from those on the working environment. In order to properly integrate these two types of environmental impacts into the total environmental impacts, it is necessary to define the identical system boundaries and select the impact category indicators at the same level as the environmental mechanism;

- System boundary: input and output data must be collected throughout the entire life cycle of a given product for both the external and working environment modules.
- Impact level: environmental impacts of a given product system must be evaluated at the same level as the environmental mechanism for both the external and working environment modules.

System boundary In the conventional LCA study, the data relevant to the external environment are collected throughout the entire life cycle. On the other hand, in general, only on-site data from the particular factory, or area, are considered for the working environment, excluding the data associated with the upstream and/or downstream processes. As pointed out, it is necessary to have the same system boundaries for both the external and working environments in order to properly integrate them. This means that the system boundary for the working environment module has to be extended from a site to the entire life cycle. In this study, it is proposed to extend the system boundary for the working environment by using the IOA which is a technique that shows how industrial sectors are infinitely interlinked through supply and use of commodities (input–output tables, The Bank of Korea 2000).

Impact level In order to integrate the environmental impacts on both the external and working environments, both have to be evaluated at the same level as the environmental mechanism. The category indicators for both

the external environment and working environment are at the endpoint level, since in this study it is intended to develop a methodology which attempts to assess the total environmental impacts at the endpoint level.

Table 1 provides a comparison between the existing methods and the proposed method in this study from the viewpoints of the intended applications, system boundary, and the type of the impacts.

2.2 Life cycle inventory analysis

In general, there are two approaches for a life cycle inventory analysis (LCI) analysis: bottom-up approach of conventional LCI method and top-down approach of IOA method (Nielsen and Weidema 2001). The latter uses the statistical data on production and consumption in individual industrial sectors in order to compile LCI tables. So, it is relatively easy to collect the related data and compile LCI tables. However, the uncertainties from the results are high since the inherent uncertainties of this approach are induced from the statistical data. On the other hand, the former uses the site-specific process data for LCI analysis. In many cases, relevant data are not available and, thus, LCI tables cannot be completed. In particular, it is difficult to collect data of occupational health and safety throughout a product's life cycle due to the absence of the information for the related parameters in conventional LCI databases. On the other hand, the uncertainties of the LCI results induced from site-specific data are lower than the uncertainties from top-down approach. This study applies 'hybrid IOA method', in the first tier level of a product's life cycle, which combines the advantages between bottom-up and top-down approaches in order to solve the issue of data availability as well as to reduce the uncertainties of LCI results. Nevertheless, the hybrid IOA method still has the uncertainties because of the use of national statistics from the second tier level of a product's life cycle.

First, site-specific gate-to-gate (GtG) data at a production or manufacturing site of a product by using bottom-up approach are constructed. The IOA method enables one to extend the GtG data to upstream processes. The inputs of the GtG data from the first tiers (technosphere inputs) are connected with the IOA method and the outputs of the GtG data (technosphere outputs) which are linked to generic LCI databases constructed by the conventional LCI method. Accordingly, the GtG data, IO table, and generic databases are combined together to compile a complete life cycle inventory. Fig. 1 illustrates the framework of the LCI method used in this study.

In particular, identifying and quantifying the inputs and outputs of upstream processes by using the IOA technology are crucial in the LCI study (Nielsen and Weidema 2001). The detailed procedures are as follows and also explained in Fig. 2:

- Construction of the GtG data from the first tier
- Classification of the GtG data to identify the final demands (Y) from each industrial sector
- Computation of the total direct and indirect requirement per each industrial sector (X) by multiplying Y with Leontief multiplier (A^{-1})

$$X = A^{-1}Y \tag{1}$$

In which, both X and Y are expressed as a unit of money (e.g., $)

- Computation of the total direct and indirect environmental interventions (M) by multiplying X with environmental intervention factors (EIF, P)

$$M = XP \tag{2}$$

In which, M is regarded as life cycle inventory (LCI) results.

Table 1 Summary of the existing and proposed method for working environment

		Chem.	IVF	IVL	MUP	STØ	EDIP	New EDIP	Proposed method
Intended application	Screening	O			O	O			
	Sector			O				O	O
	Process		O				O		O
System boundary	Life cycle	O	O	O	O		O	O	O
	Some process					O			
Type of impacts	Exposure (measurement)		O						O
	Exposure (estimate)	O	O		O	O	O	O	O
	Effect	O	O	O			O		O

Chem. Chemiewinkel University of Amsterdam, *IVF* Swedish Institute of production engineering research, *IVL* Swedish environmental research institute, *MUP* Danish Materials Technology Program, *STØ* Østfold Research Foundation in Norway, *EDIP* Danish Environmental Agency

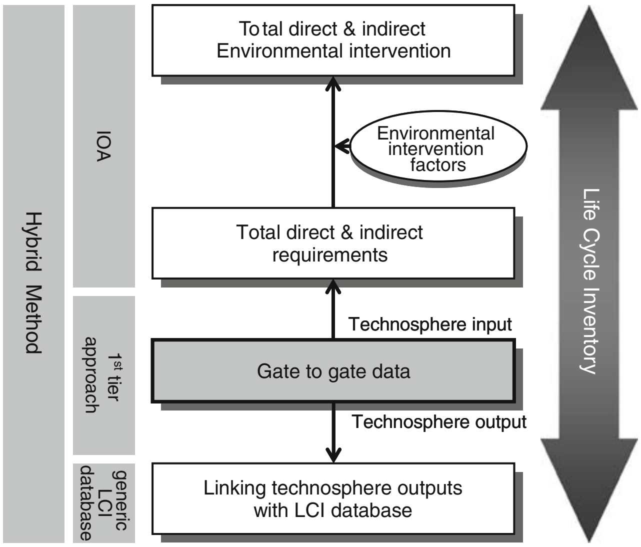

Fig. 1 Framework for hybrid IOA method

As shown in Eq. (2), the EIFs (P) have to be developed to calculate the total direct and indirect environmental interventions and to compile the LCI table. In this study, the EIFs of each industrial sector for resource use, air emissions, and water emissions are developed for the external environment. And, the number of workers affected by specific hazardous items (WHI) and the number of workers proven to magnitude of disability (WMD) are collected and analyzed for each industrial sector as the EIFs of occupational health and occupational safety for the working environment. In this study, the EIFs of the inventory parameters associated with the working environment, as well as the external environment are generated as follows;

Resource use The EIFs of resource use are defined as the total domestic 'quantity of resources transported' of i resource (TDR_i) per gross domestic product (GDP) of j industrial sector. Here, the resource category includes anthracite coal, bituminous coal, crude oil, natural gas, iron ore, and so on.

$$\mathrm{EIF}(r)_{ij} = \frac{\mathrm{TDR}_{ij}}{\mathrm{GDP}_j} \tag{3}$$

Air emissions The EIFs of air emissions are defined as the total national amount (TNA) of i air emission per GDP of j industrial sector. The air emissions are classified into two categories; conventional air emissions such as greenhouse gasses, NO_x and SO_x, and toxic substances. The TNAs of conventional air emissions are computed by multiplying the amount of k fuel consumed in j industrial sector (AF_{ijk}) with the amount of i emission emitted from k fuel used in j industrial sector (F_{jk}) as shown in Eq. (4). The amounts of fuels used in each industrial sector are collected from the

data category	name	unit	amount	data category	name	unit	amount
material	SM	kg	9.80E-01	air emission	ammonia	kg	2.30E-06
ancially material	...	kg	...		...	kg	...
	...	kg	...	OH	noise	pe	1.10E-08
	...	kg	...		...	pe	...
	elec.	kwh	2.50E-01	OS	MOD(I)	pe	3.20E-08
	...	kg	...		...	pe	...

Industrial Sector	amount	unit cost	final demand	data category	name	unit	amount
agriculture				air emission	ammonia	kg	2.30E-06
...					...	kg	...
chem. Production	9.80E-01	1.00E+01	9.80E + 00	OH	noise	pe	1.10E-08
...	...				...	pe	...
power geneneration	2.50E-01	1.00E-01	2.50E -02	OS	MOD(I)	pe	3.20E-08
...	...				...	pe	...

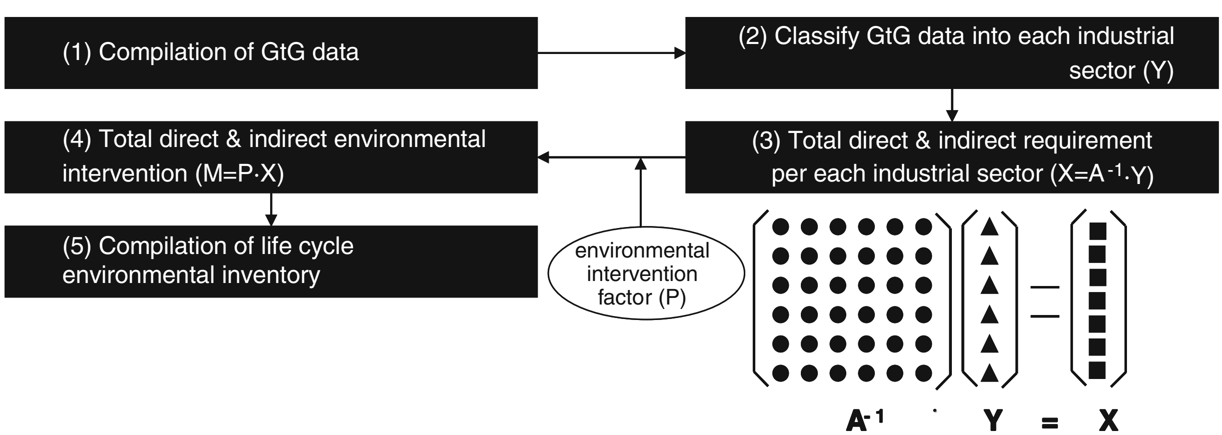

Fig. 2 Procedure for implementing IOA

Korea Energy Management Corporation (The Korea Energy Management Corporation, KEMCO 2002).

$$\mathrm{EIF}(a)_{ij} = \frac{\mathrm{TNA}(a)_i}{\mathrm{GDP}_j} = \frac{\sum_k \left(F_{jk} \times AF_{ijk}\right)}{\mathrm{GDP}_j} \tag{4}$$

In addition, the TNAs of toxic substances reported in the Pollutant Release and Transfer Registers (PRTR) in Korea are calculated by extrapolating the TNAs in the Netherlands. As shown in Eq. (5), the TNAs in Korea are calculated by multiplying the TNAs in the Netherlands with the ratio of the GDPs between Korea and the Netherlands, assuming that the industrial structures of the two countries are similar.

$$\mathrm{TNA}(kr) = \mathrm{TNA}(nl) \times \frac{\mathrm{GDP}_{kr}}{\mathrm{GDP}_{nl}} \tag{5}$$

Water emissions As shown in Eq. (6), The EIFs of water emissions are defined as the TNA of i water emission (TOW_{ij}) per GDP of j industrial sector. The EIFs of water emissions are classified into two data categories; conventional water emissions such as BOD, COD, SS, T-N, and T-P, and toxic substances. The published data of water emissions in the Ministry of Environment (MOE) are used for the TNAs of BOD, COD, SS, T-N, and T-P, respectively. For toxic substances, Eq. (5) is used to calculate the TNAs.

$$\mathrm{EIF}(w)_{ij} = \frac{\mathrm{TOW}_{ij}}{\mathrm{GDP}_j} \tag{6}$$

Occupational health The EIFs of occupational health are defined as the number of workers affected by i hazardous items (WHI_{ij}) per GDP of j industrial sector. The hazardous items are classified into physical factors, chemical factors and biological factors. Physical factors include noise, vibration, particles, and others, chemical factors include organic solvents, specific chemicals, metals, and heavy metals. Biological factors include each kind of epidemic. This study only considered the hazardous items by both physical and chemical factors because biological factors generally are regarded as occupational diseases. The definition of the WHI is the number of potential workers who will be actual patients. The WHI data are collected from the Korea Occupational Safety and Health Agency (KOSHA; Korea Occupational Safety & Health Agency 2002; Ministry of Labor 2002).

$$\mathrm{EIF}(\mathrm{OH})_{ij} = \frac{\mathrm{WHI}_{ij}}{\mathrm{GDP}_j} \tag{7}$$

Occupational safety The EIFs of occupational safety are defined as the number of workers at i magnitude of disability (WMD_{ij}) per GDP of j industrial sector. The magnitude of disability (MOD) is classified into 15 levels, including death. Here, the definition of the WMD is the number of workers with actual occupational disease, not potential disease by occupational accidents, such as fire and explosion. The WMD data, that is, damage data, are collected from the KOSHA (Korea Occupational Safety & Health Agency 2002; Ministry of Labor 2002).

$$\mathrm{EIF}(\mathrm{OS})_{ij} = \frac{\mathrm{WMD}_{ij}}{\mathrm{GDP}_j} \tag{8}$$

2.3 Life cycle impact assessment (LCIA)

The life cycle impact assessment (LCIA) is conducted according to the framework of ISO 14042. As a first step, appropriate impact categories are considered and selected for both the external environment and working environment. The impact categories selected for the external environment include cancer, respiratory disease, radiation poisoning, ozone depletion, global warming, eco-toxicity, acidification, eutrophication, and resource use. For the impact categories of the working environment, occupational health and safety figure are selected for this study. The LCI results are assigned to each impact category. For example, vibration, noise, particles, organic solvents, specific chemicals, heavy metals, and others are the inventory parameters assigned to the occupational health category. In order to assess the impacts at the endpoint level, not only exposure analysis but also damage analysis are included in this study.

2.3.1 Characterization

As explained in the general requirements, the category indicators for both the external environment and working

Fig. 3 Characterization procedure for occupational health and safety

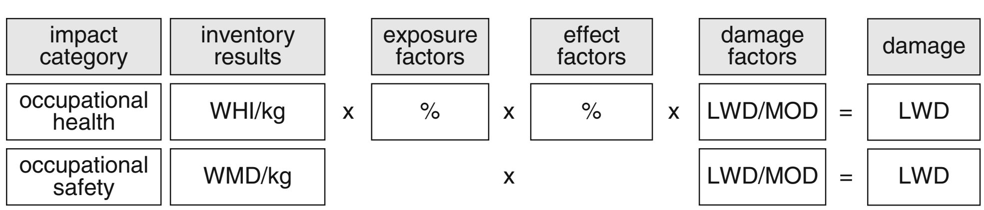

Table 2 Damage factors per magnitude of disability

Magnitude of disability	I	II	III	IV	V	VI	VII
LWD	7,500	7,500	5,500	4,000	4,000	3,000	2,200
Magnitude of disability	VIII	IX	X	XI	XII	XIII	XIV
LWD	1,500	1,000	600	400	200	100	50

environment are chosen at the endpoint level. The number of disability-adjusted life year (DALY) and the potentially affected fraction (PAF) are used as the category indicators to evaluate the damage to human health and eco-system quality in the external environment, respectively. The Eco-indicator 99 method is used for the characterization of the external environment (Goedkoop and Spriensma 2000). For occupational health and safety, LWD is used as the category indicator to evaluate the damage to human health in the working environment. In order to use DALY instead of LWD for occupational health and safety, the disability data on each disease for occupational health and each accident for occupational safety are required. Since, however, they are not available, at present, it is difficult to use DALYs for working environment. The characterization procedures for occupational health and safety are shown in Fig. 3 and explained below.

Occupational health As illustrated in Fig. 3, the LWD for occupational health is calculated in three steps consisting of exposure analysis, effect analysis, and damage analysis. The exposure factors, effect factors, and damage factors are generated in this study, and are needed to carry out the exposure analysis, effect analysis, and damage analysis.

Equation (9) defines the exposure factors (ExF_i), explained as the possibility that the WHI generated by i hazardous items such as noise, vibration, specific chemicals etc. will result in actual occupational diseases (OD_i).

$$\mathrm{ExF}_i = \frac{\mathrm{OD}_i}{\mathrm{WHI}_i} \tag{9}$$

In Eq. (10), the effect factors (EF_{ij}) are defined as the possibility that real occupational disability by i hazardous item (OD_i) will be shown by OD of j MOD. MOD is classified from levels 1 to 14, including death.

$$\mathrm{EF}_{ij} = \frac{\mathrm{OD}_{ij}}{\mathrm{OD}_i} \tag{10}$$

The damage factors (DF_j) are defined as LWD for each MOD, and they are obtained from the published data of the KOSHA as shown in Table 2. The LWD_{tot}, which is the

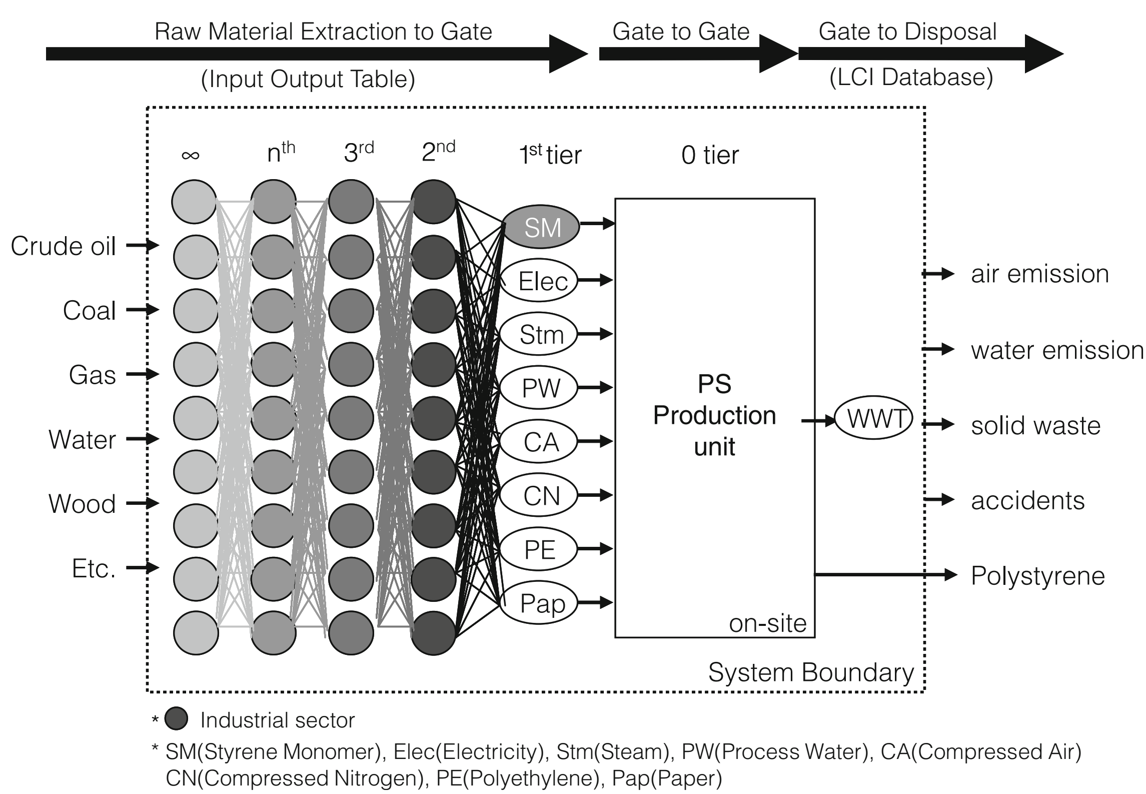

Fig. 4 Overview of the hybrid IOA method used for PS production system

Table 3 LCI results assigned to occupational health and safety

Data category	Hazardous items (*i*)	Unit	Number of workers affected
Occupational health	Vibration	WHI	1.7E−06
	Noise	WHI	2.0E−04
	Others	WHI	4.8E−08
	Particles	WHI	3.7E−05
	Organic solvents	WHI	6.0E−06
	Specific chemicals	WHI	4.2E−06
	Metals and heavy metals	WHI	2.5E−06
Occupational safety	MOD (death)	WMD	4.2E−05
	MOD (I)	WMD	6.5E−07
	MOD (II)	WMD	1.2E−06
	MOD (III)	WMD	6.1E−06
	MOD (IV)	WMD	6.3E−06
	MOD (V)	WMD	6.3E−06
	MOD (VI)	WMD	2.8E−05
	MOD (VII)	WMD	2.0E−05
	MOD (VIII)	WMD	4.1E−05
	MOD (IX)	WMD	1.9E−05
	MOD (X)	WMD	8.1E−05
	MOD (XI)	WMD	5.7E−05
	MOD (XII)	WMD	9.6E−05
	MOD (XIII)	WMD	3.0E−05
	MOD (XIV)	WMD	1.2E−04

total damage to occupational health, is the characterization result for occupational health at the endpoint level and is calculated by multiplying WHI, exposure factors, effect factors and damage factors as shown in Eq. (11).

$$\mathrm{LWD}_{tot} = \sum_j \sum_i \left(\mathrm{WHI}_i \times \mathrm{ExF}_i \times \mathrm{EF}_{ij} \times \mathrm{DF}_j\right) \tag{11}$$

Occupational safety The procedure to calculate the LWD for occupational safety is somewhat different from that for occupational health, as shown in Fig. 3. That is to say, it is not necessary to conduct the exposure analysis and effect analysis because the data collected for occupational safety already represent the WMD, which is the number of real occupational patients affected by occupational accidents. Therefore, the total damage to occupational safety can be calculated by directly multiplying the WMD of *j* MOD by the EF for *j* MOD as shown in Eq. (12).

$$\mathrm{LWD}_{\mathrm{tot}} = \sum_j \left(\mathrm{WMD}_j \times \mathrm{EF}_j\right) \tag{12}$$

2.3.2 Normalization

Normalization is a step which enables one to understand the relative magnitude of the characterized results of each impact category. In order to calculate the normalization, it is necessary to define appropriate normalization references. While the normalization references developed in Eco-

Table 4 Results of exposure analysis for occupational health

Hazardous items (*i*)	LCI results (WHI_i)	Exposure factor (ExF_i)	Results of exposure analysis (OD_i)
Noise	2.0E−04	6.4E−03	1.3E−06
Vibration	1.7E−06	1.3E−02	2.2E−08
Others	4.8E−08	1.1E−01	5.1E−09
Particles	3.7E−05	5.8E−01	2.1E−05
Organic solvents	6.0E−06	1.7E−02	1.0E−07
Specific chemicals	4.2E−06	1.7E−02	7.1E−08
Metals & heavy metals	2.5E−06	2.1E−02	5.4E−08

Table 5 Results of effect analysis for occupational health

MOD_j	Noise			Particles			. . .
	OD_i	EF_{ij}	OD_{ij}	OD_i	EF_{ij}	OD_{ij}	. . .
Death	1.3E−06	0.0E+00	0.0E+00	2.1E−05	4.1E−01	8.7E−06	. . .
I		0.0E+00	0.0E+00		0.0E+00	0.0E+00	. . .
. . .		. . .	. . .		. . .	. . .	. . .
XIV		1.8E−01	2.2E−07		0.0E+00	0.0E+00	. . .

indicator 99 are used for the impact categories of the external environment, those for occupational health and safety are developed in this study. The normalization reference for occupational health is calculated as the total national LWD from the occupational diseases by hazardous items during the given period of time ($LWD_{tot\text{-}OH}$) divided by the total number of the workers (WO_{tot}), as shown in Eq. (13).

$$NR_{OH} = \frac{LWD_{tot-OH}}{WO_{tot}} \tag{13}$$

For occupational safety, the $LWD_{tot\text{-}OH}$ in Eq. (13) is substituted for the total national LWD from the occupational accidents ($LWD_{tot\text{-}OS}$) to generate the normalization reference.

3 Implementation of life cycle assessment

A case study is presented below to illustrate the applicability of the proposed method for the integration of the working environment module into the conventional LCA framework focusing on the characterization procedures for the working environment. For the external environment, the characterization procedures of the Eco-indicator 99 method are used, since no method which attempts to assess the impacts on the external environment at the endpoint level is available in Korea (Goedkoop and Spriensma 2000). In order to identify the total environmental impacts, it is necessary to evaluate both external and working environmental impacts at the endpoint level, but no method to evaluate external environmental impacts at the same level is available in Korea. Therefore, the Eco-indicator 99 was used instead as a method to evaluate external environmental impacts, and this is the limitation of the study. The goal of the case study is to evaluate the impacts on the working environment as well as on the external environment associated with a polystyrene (PS) production system in a Korean petrochemical company. The functional unit for input/output quantification basis is set at 1 ton of PS production.

Figure 4 shows the implementation procedures of the hybrid IOA method used for the LCI study of the PS production system. As the first step, site-specific process data from the PS manufacturing site are collected to compile GtG data. Site-specific process data include not only raw materials, energy and utilities, and process emissions, but also the chemical and physical data for occupational health such as noise, vibration, particles, organic solvents, specific chemicals, heavy metals and others, and the MODs classified into 15 levels for occupational safety.

The inputs to the GtG data are assigned to 28 industrial sectors, which are the basic industrial sectors classified by The Bank of Korea (2000). The total direct and indirect requirements per industrial sector of PS production system are compiled by multiplying the assigned GtG data by the Leontief inverse multiplier as presented in Eq. (1) and, then, they are multiplied by the EIFs to give the LCI results, as shown in Eq. (2). This study uses Leontief multiplier that treats import commodities as domestic products with the assumption that import commodities are produced in the same way as domestic ones. This assumption can be problematic in open economics with large imports and exports. Suh and Gjalt Huppes suggested that a possible solution to the import assumption is a multi-regional IOA

Table 6 Characterization results for occupational health (damage)

MOD_j	DF_j	Noise		Particles		. . .	LWD_{tot}
		OD_{ij}	LWD_i	OD_{ij}	LWD_i		
Death	7500	0.0E+00	0.0E+00	8.7E−06	6.6E−02	. . .	6.6E−02
I	7500	0.0E+00	0.0E+00	0.0E+00	0.0E+00	. . .	0.0E+00
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
XIV	50	2.2E−07	1.1E−05	0.0E+00	0.0E+00	. . .	1.2E−05
Total	-	-	2.2E−05	-	6.9E−02	. . .	7.0E−02

Table 7 Characterization results for occupational safety (damage)

Hazardous items (i)	LCI results (WMD_i)	Damage factor (LWD_i)	LWD_{tot}
MOD (death)	4.2E−05	7,500	3.2E−01
MOD (I)	6.5E−07	7,500	4.9E−03
MOD (II)	1.2E−06	7,500	9.2E−03
MOD (III)	6.1E−06	5,500	3.4E−02
MOD (IV)	6.3E−06	4,000	2.5E−02
MOD (V)	6.3E−06	4,000	2.5E−02
MOD (VI)	2.8E−05	3,000	8.3E−02
MOD (VII)	2.0E−05	2,200	4.3E−02
MOD (VIII)	4.1E−05	1,500	6.1E−02
MOD (IX)	1.9E−05	1,000	1.9E−02
MOD (X)	8.1E−05	600	4.9E−02
MOD (XI)	5.7E−05	400	2.3E−02
MOD (XII)	9.6E−05	200	1.9E−02
MOD (XIII)	3.0E−05	100	3.0E−03
MOD (XIV)	1.2E−04	50	5.9E−03
Total			7.2E−01

model (Nielsen and Weidema 2001). However, a multi-regional IOA model is very difficult to apply since not only the number of industrial sectors but also the boundaries between industrial sectors in each country are different. Therefore, in this study, import commodities are treated as domestic products in spite of their geographical uncertainties.

Table 3 shows the LCI results on the PS production system in Korea assigned to occupational health and safety. Here, the units of occupational health and occupational safety are WHI and WMD, respectively.

The LCIA was conducted to evaluate the environmental impacts associated with the PS production system. The characterization procedures for occupational health consist of exposure analysis, effect analysis and damage analysis. As shown in Table 4, the results of exposure analysis for each hazardous item for occupational health were calculated by multiplying the LCI result with exposure factor. In the case of noise, for example, the result of exposure analysis (OD_i) is calculated as 1.3E−06, which means that 1.3E−06 workers per functional unit have the possibility of contracting occupational disabilities.

Table 5 shows the results of effect analysis for occupational health. In the case of noise, the result of effect analysis, 1.3E−06 times effect factor on 14th MOD (ExF_{ij}), 1.8E−01 is 2.2E−07. This result means that 2.2E−07 workers exposed potential occupational noise will have developed occupational disabilities in accordance with the 14th MOD.

The results of damage analysis, which is the final step of the characterization procedures for occupational health, were obtained from the results of effect analysis by multiplying them by the damage factor. In the case of noise, the damage to workers shown by 14th real occupation (LWD_{14}), 1.1E−05 was calculated by multiplying the result of effect analysis, 2.2E−07 by the damage factor of 14th MOD, 50. This result means that the worker at 14th MOD per functional unit will lose 1.1E−05 working days because of occupational disease. According to Table 6, domestic workers will lose 7.0E−02 working days per functional unit.

As illustrated in Eq. (12), the damage to occupational safety is calculated by multiplying the number of workers affected by occupational accidents presented in Table 3 by the damage factors. Table 7 indicates that the damage of occupational accidents is calculated as 7.2E−01 per functional unit. This result means that the domestic workers will lose 7.2E−01 working days as the result of occupational accidents.

Normalization is conducted to compare the relative magnitudes between the damages to occupational health

Table 8 Normalized results for working environment

Impact category	Damage (LWD)	Normalization reference in 2001 (LWD/worker)	Normalization results (worker)
Occupational health	7.0E−02	4.6 E−01	1.5E−01
Occupational safety	7.2E−01	6.2 E+00	1.2E−01

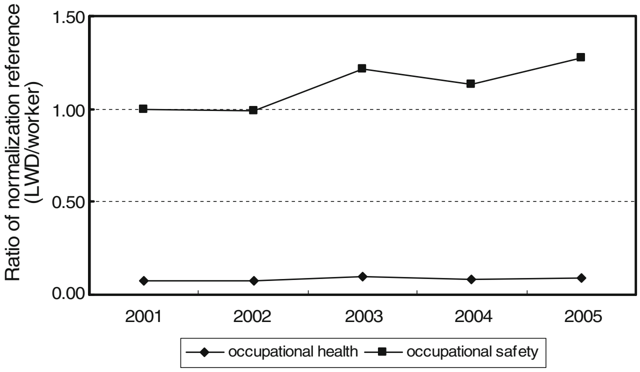

Fig. 5 Ratio of normalization references for occupational health and safety

and occupational safety. According to Eq. (13), the normalization references for occupational health and safety in Korea are obtained as 4.6E−01 (LWD/worker) and 6.2E+00 (LWD/worker), respectively. This means that, in 2002, one worker in Korea lost 4.6E−01 and 6.2E+00 working days from the occupational diseases and accidents, respectively. By using the normalization references, the normalized results for occupational health and safety are calculated as 1.5E−01 and 1.2E−01 workers, respectively. Thus, in the present case study, the damage for occupational health is relatively more significant than that for occupational safety as shown in Table 8

In order to check the variability of the normalization values for occupational health and safety over the years, their trends are examined. Figure 5 shows that the values of the normalization reference for both occupational health and safety have not changed significantly.

Table 9 shows the relative magnitudes of each life cycle stage to the normalized impacts of eight impact categories, respectively. The life cycle stages of the current PS production system are divided into pre-manufacturing and manufacturing stages. Then, the life cycle stages are divided further into unit processes to examine and identify the contribution from each unit process. The manufacturing stage consists of the polymerization of PS, pelletizing process, and packaging process, while the pre-manufacturing stage includes the preparation of the raw material, styrene monomer (SM), chemicals, and containers. It is found that the contribution of the pre-manufacturing stage is overwhelming for all impact categories. However, it is shown that the contribution of the manufacturing stage is relatively larger than those in other categories. The contribution of the manufacturing stage is less than 1% for all impact categories, except for occupational health category. The relative large contribution (6.9%) of the manufacturing stage to the total occupational health damage is due to the particles from the palletizing and packaging processes. Therefore, it is suggested to reduce the amount of particles occurring from the manufacturing stage with appropriate treatment processes or abatement technologies in order to improve the impacts on occupational health category in the working environment.

In addition, if it is assumed that each category is equally important, the impacts on occupational health and safety are larger than those on the external environment. These results indicate that it is important to include the working environment in LCA framework in order to avoid false optimization.

4 Conclusions

This study is intended to develop a total environmental assessment methodology which enables one to appropriate-

Table 9 Normalized LCIA profiles of PS production system

Impact category	Pre-manufacturing stage			Manufacturing stage	Total
	SM	Ethyl benzene	Others		
ARD	1.7E−03 (99.9%)	1.9E−05 (0.1%)	6.6E−06	4.4E−06	1.7E−03 (100.0%)
GW	5.3E−04 (96.2%)	2.2E−05 (3.7%)	3.7E−07	1.0E−06 (0.1%)	5.5E−04 (100.0%)
OD	6.7E−07 (97.7%)	1.2E−08 (2.0%)	0.0E+00	1.6E−09 (0.3%)	6.9E−07 (100.0%)
POC	1.1E−04 (93.3%)	7.4E−06 (6.2%)	1.2E−08	6.2E−07 (0.5%)	1.2E−04 (100.0%)
AC	1.4E−04 (94.6%)	7.6E−06 (5.1%)	6.5E−08	3.9E−07 (0.3%)	1.5E−04 (100.0%)
EU	9.9E−05 (95.6%)	4.6E−06 (4.2%)	3.4E−08	2.5E−07 (0.2%)	1.0E−04 (100.0%)
OH	1.4E−01 (84.4%)	1.4E−02 (8.7%)	3.9E−05	1.1E−02 (6.9%)	1.6E−01 (100.0%)
OS	1.1E−01 (95.6%)	4.6E−03 (3.8%)	2.0E−05	7.5E−04 (0.6%)	1.2E−01 (100.0%)

ARD abiotic resource depletion, *GW* global warming, *OD* ozone depletion, POC photochemical oxidant creation, AC acidification, EU eutrophication, OH occupational health, OS occupational safety

ly integrate the working environment module into the conventional LCA framework. The hybrid IOA method is used to extend the system boundaries of both the external environmental module and the working environmental module to the entire life cycle of a product system, and it is used to solve the issue of data availability in the computational LCA as well as to reduce the uncertainties of the LCI results in the IOA based LCA method. Nevertheless, the uncertainties still exist in the LCI results of the hybrid IOA method, since it uses the national statistical data from the second tier level of a product's life cycle. The environmental impacts at the endpoint level are assessed for both the external environment and the working environment.

For the LCIA study, the characterization procedures for the working environment are developed, selecting LWD as a category indicator on occupational health and safety. While the LWD for occupational health is calculated in three steps: exposure analysis, effect analysis, and damage analysis, the LWD for occupational safety is calculated without exposure analysis and effect analysis, since the data of the WMD which is the number of real patients affected by occupational accidents is already publicly available. Then, the total national LWD from occupational diseases and occupational accidents per a worker in Korea is used as the normalization reference for occupational health and safety, respectively. On the other hand, DALY and PAF are used as the category indicators to evaluate the damage to human health and eco-system quality in the external environment, respectively. It would be more convenient to use the same category indicator for both external environment and working environment. At present, in Korea, however, because of the absence of the disability data on each disease for occupational health and each accident for occupational safety, it is difficult to use DALY as a category indicator for working environment.

References

Antonsson A-B, Carlsson H (1994) Two methods to integrate work environment in LCA, Proceedings of the 3rd international workshop on life cycle assessment and the working environment

Antonsson AB, Helene Carlsson H (1995) The basis for a method to integrate work environment in life cycle assessment. J Cleaner Prod Vol. 3, No. 4, Swedish environmental research institute (IVL)

Bengtsson G, Berglund R (1996) Life cycle assessments including the working environment. Swedish Institute of production engineering research (IVF)

Goedkoop M, Spriensma R (2000): The Eco-indicator 99—a damage oriented method for life cycle impact assessment. Pré Consultants

Hauschild M, Wenzel H (1998) Environmental assessment of products. Chapman & Hall, London, UK vol. 2, 465–508

Honkasalo A (2000) Occupational health and safety and environmental management systems. Environmental Science & Policy, 39-45

International Standard ISO 14040 (2006) Environmental management—life cycle assessment—principles and framework. International Organization for Standardization, Geneva, Switzerland

Korea Occupational Safety & Health Agency (2002) Survey of occupational accidents and diseases 2001

Ministry of Labor (2002) Results on health examination of a worker in 2000. Republic of Korea

Nielsen AM, Weidema BP (2001) Input/output analysis—shortcuts to life cycle data? Environmental Project No. 581

Nilsson M, Antonsson AB (1998) Introduction on why and how to integrate work environment in Life cycle assessment. Occup Hyg 4:215–222

Potting J, Møller BT, Jensen AA (1998) LCANET Theme report—work environment and LCA, Centre of Environmental Science (CML), Leiden University

Poulsen PB, Jensen AA (2004) Working environment in life cycle assessment, SETAC

Rønning A, Hanssen OJ, Møller H. (1995) Environmentally sound product development of offshore coatings. Østfold Research Foundation (STØ), ISBN: 82-7520-215-9

Schmidt A, Drabæk I, Midtgaard U (1994) Integrated environmental and occupational assessment of new materials. The Danish Materials Technology Programme (MUP)

Terwoert J (1994) Workshop paper life cycle assessment and the working environment. Chemiewinkel of the University of Amsterdam

The Bank of Korea (2000) Input–output tables (2000)

The Korea Energy Management Corporation (KEMCO) (2002) Energy Consumption statistics